TREDI 2022
The 17th "Trento" Workshop on Advanced Silicon Radiation Detectors
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University of Freiburg (Virtual)

Present and future development of thin silicon sensors for extreme fluences

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The Goals

- ➢ Measure the properties of silicon sensors at fluences above 10^{16} n_{eq}/cm^2
- ➢ Design planar silicon sensors able to work in the fluence range $10^{16} – 10^{17}$ n_{eq}/cm^2
- ➢ Estimate if such sensors generate enough charge to be used in a detector exposed to extreme fluences

⇒ **The R&D activity has started**

The Challenge

Difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2 due to:

- defects in the silicon lattice structure → increase of the dark current
- trapping of the charge carriers → decrease of the charge collection efficiency
- change in the bulk effective doping → impossible to fully deplete the sensors

A new Sensor Design

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The ingredients to overcome the present limits above 10^{16} n_{eq}/cm^2 are:

1. **saturation** of the radiation damage effects above $5 \cdot 10^{15}$ n_{eq}/cm^2
2. the use of **thin** active substrates (20 – 40 μm)
3. **extension** of the charge carrier multiplication up to 10^{17} n_{eq}/cm^2

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The whole research program is performed in collaboration with FBK
In the following, EXFLU0 and EXFLU1 will refer to two FBK productions of sensors

The State-of-the-Art

In 2020, INFN awarded for funding a 2 years grant for young researchers to **develop, produce, irradiate and study thin silicon sensors**

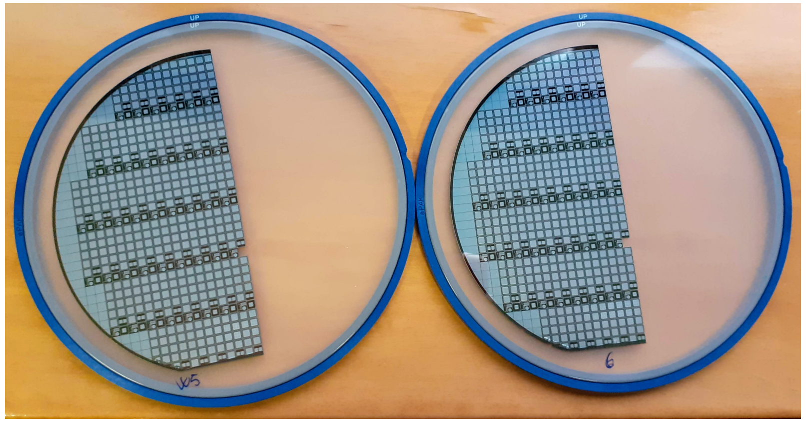
→ The *Silicon Sensor for Extreme Fluences (eXFlu)* project

Thin LGAD wafers have been produced at FBK

→ EXFLU0 production

- ▻ 2 different wafer thicknesses: **25 & 35 μm**
- ▻ epitaxial substrates
- ▻ **single pads** and 2×2 arrays

Released at the end of 2020



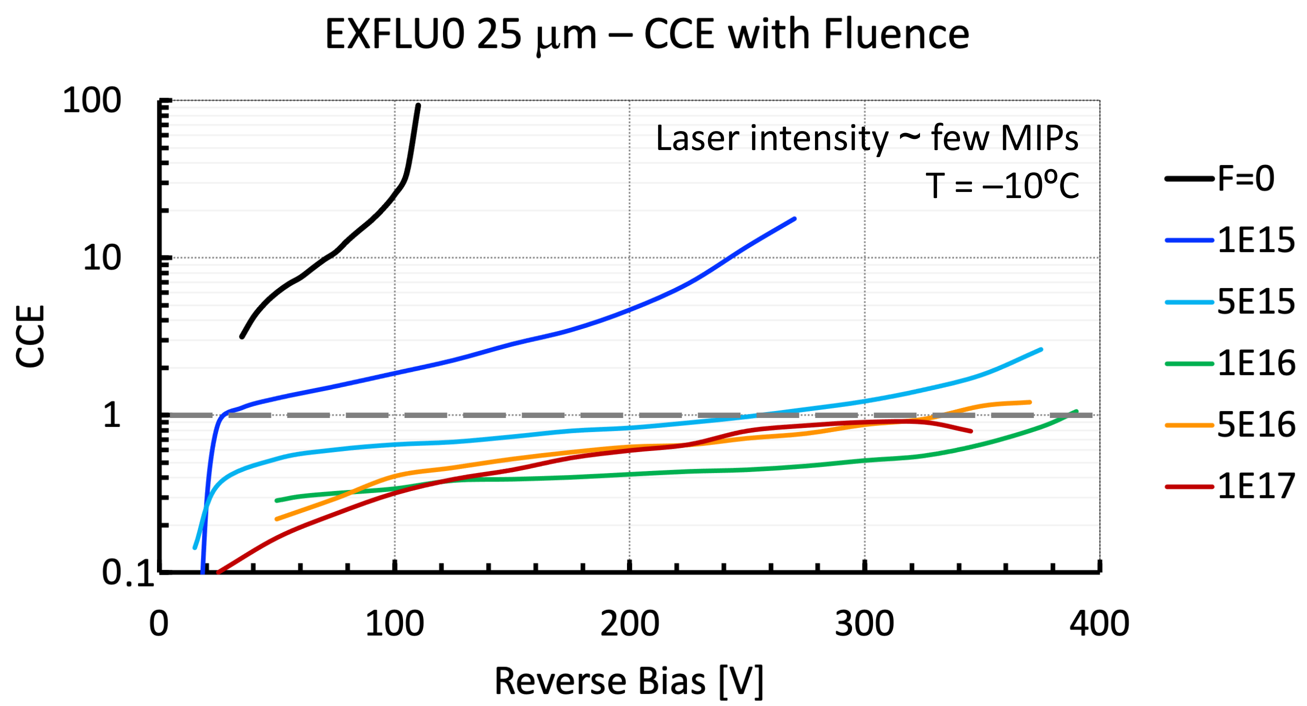
EXFLU0 sensors have been irradiated at JSI, Ljubljana, to 5 different fluences 10^{15}, $5{\cdot}10^{15}$, 10^{16}, $5{\cdot}10^{16}$, 10^{17} n_{eq}/cm^2

For more details see

- ➠ l.infn.it/exflu
- ➠ indico.cern.ch/event/896954/contributions/4106324/
- ➠ indico.cern.ch/event/1074989/contributions/4601953/

25 μm LGAD Signal at Different Fluences

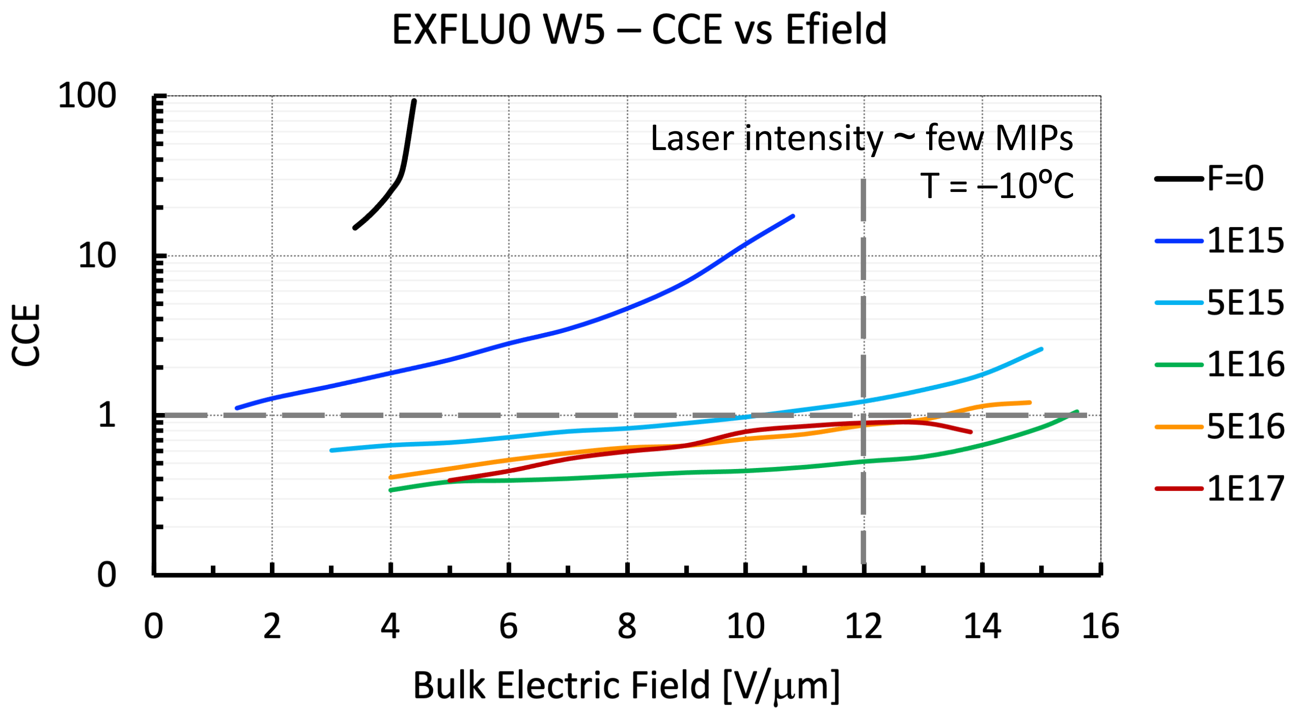
Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences



- The LGAD multiplication mechanism ceases existing at ~ $5 \cdot 10^{15}$ n_{eq}/cm^2
- From 10^{16} to 10^{17} n_{eq}/cm^2 the collected signal is roughly constant
- At high bias the signal increases due to internal gain, but does not reach the minimum charge required by the electronics

25 µm LGAD Signal vs Electric Field

Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus as a function of the electric field in the depleted bulk region



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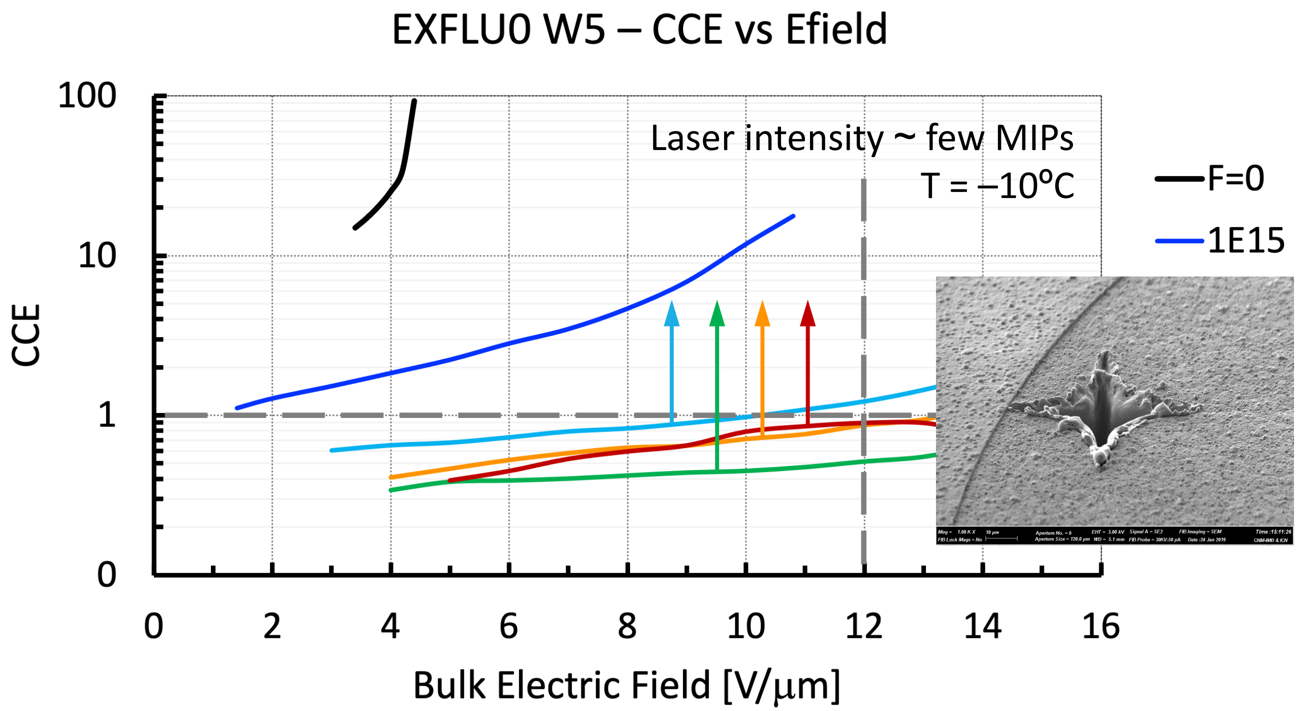
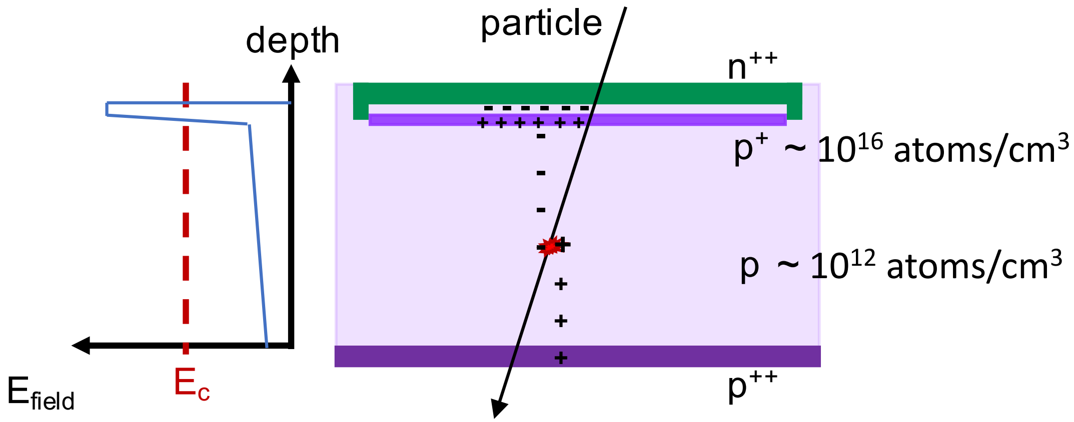
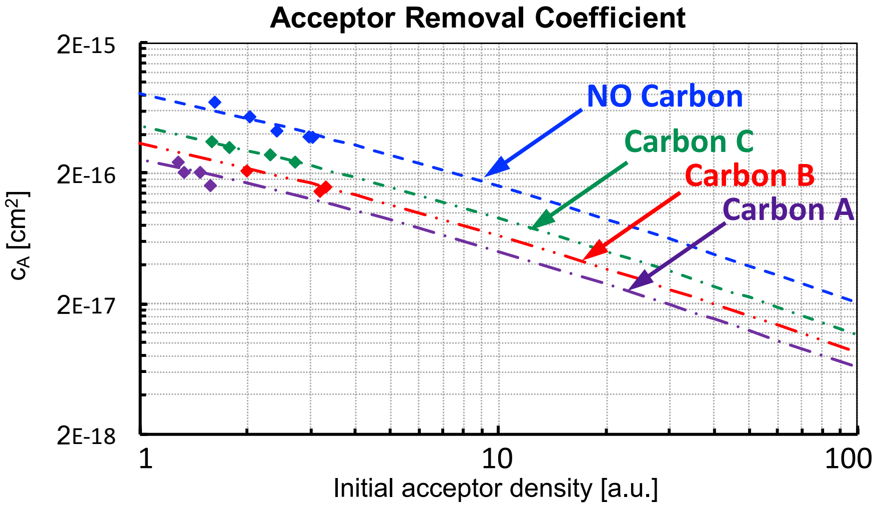


- Only data points where the sensors are fully depleted are considered here
- For electric fields above 12 V/μm, thin silicon sensors undergo fatal death once exposed to particle beams
  → Single-Event Burnout
  [indico.cern.ch/event/861104/contributions/4513238/]

→ Necessary to increase the radiation tolerance of the gain mechanism above 10^{15} n_{eq}/cm^2

Gain Removal Mechanism in LGADs





The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

$$p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}$$

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms

[M. Ferrero et al., doi:10.1016/j.nima.2018.11.121]

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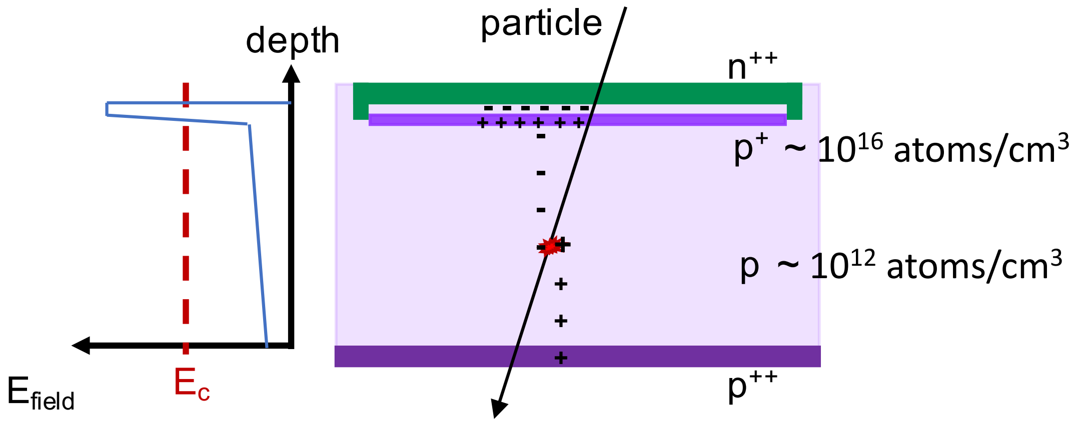

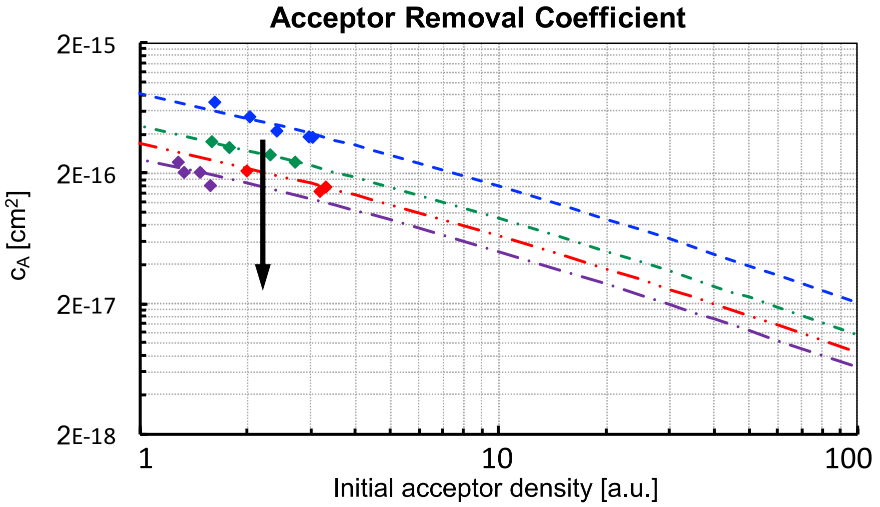

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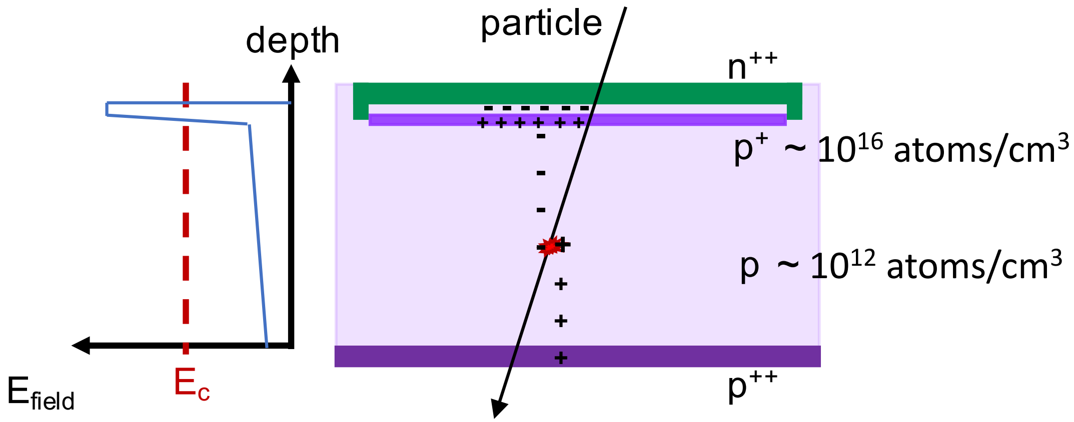
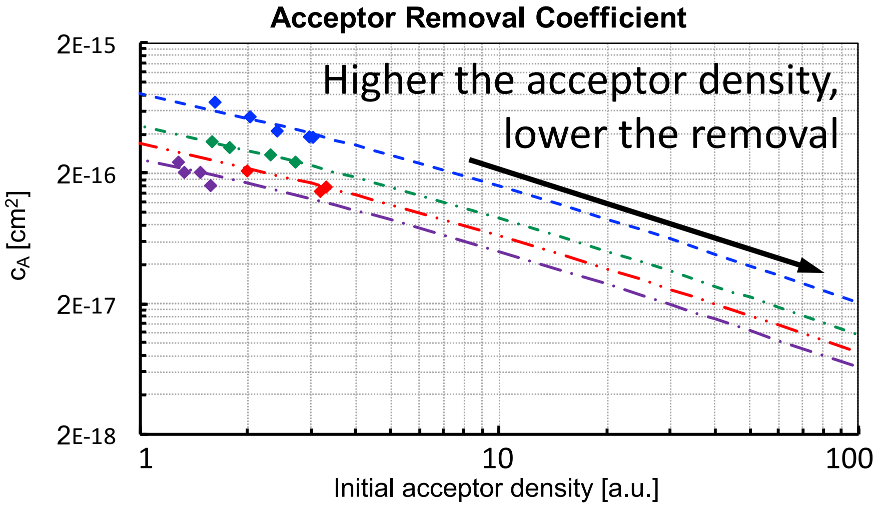
R&D to further mitigate the removal
of the acceptor atoms will be pursued

Towards a Radiation Resistant Design





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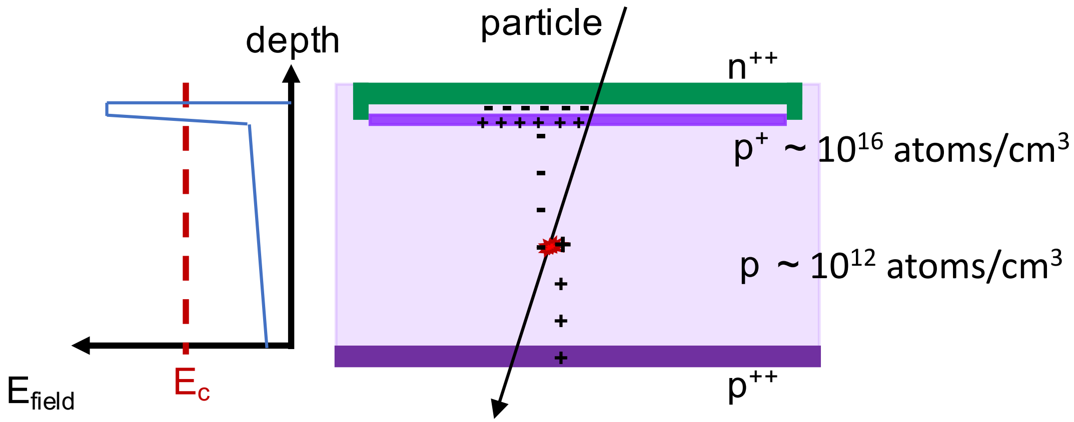

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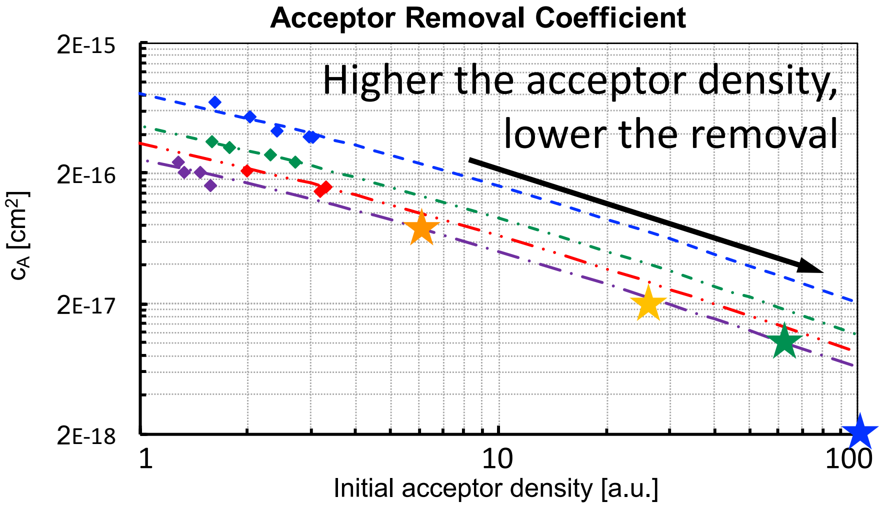
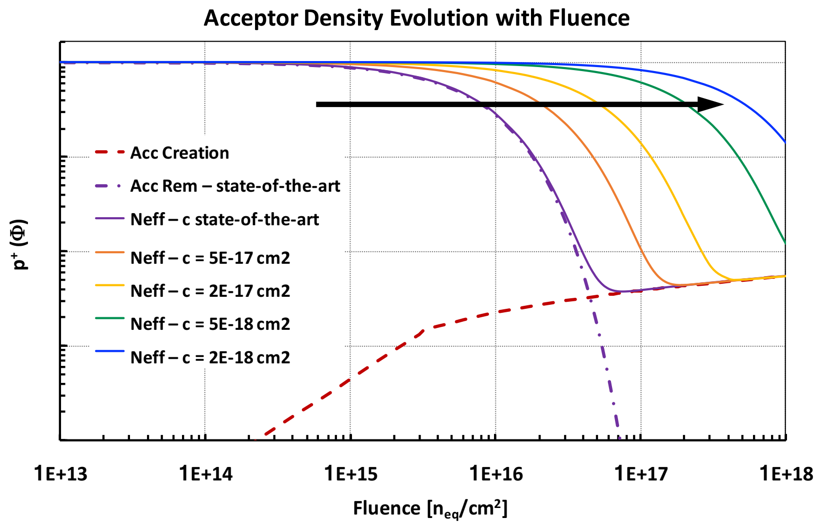




Lowering c_A extends the gain layer survival up to the highest fluences

The EXFLU1 Production at a Glance

A new production of thin LGAD is about to start at the FBK foundry ⇒ EXFLU1

The EXFLU1 production at FBK will explore different innovation strategies to extend the radiation tolerance of silicon sensors up to the extreme fluences:

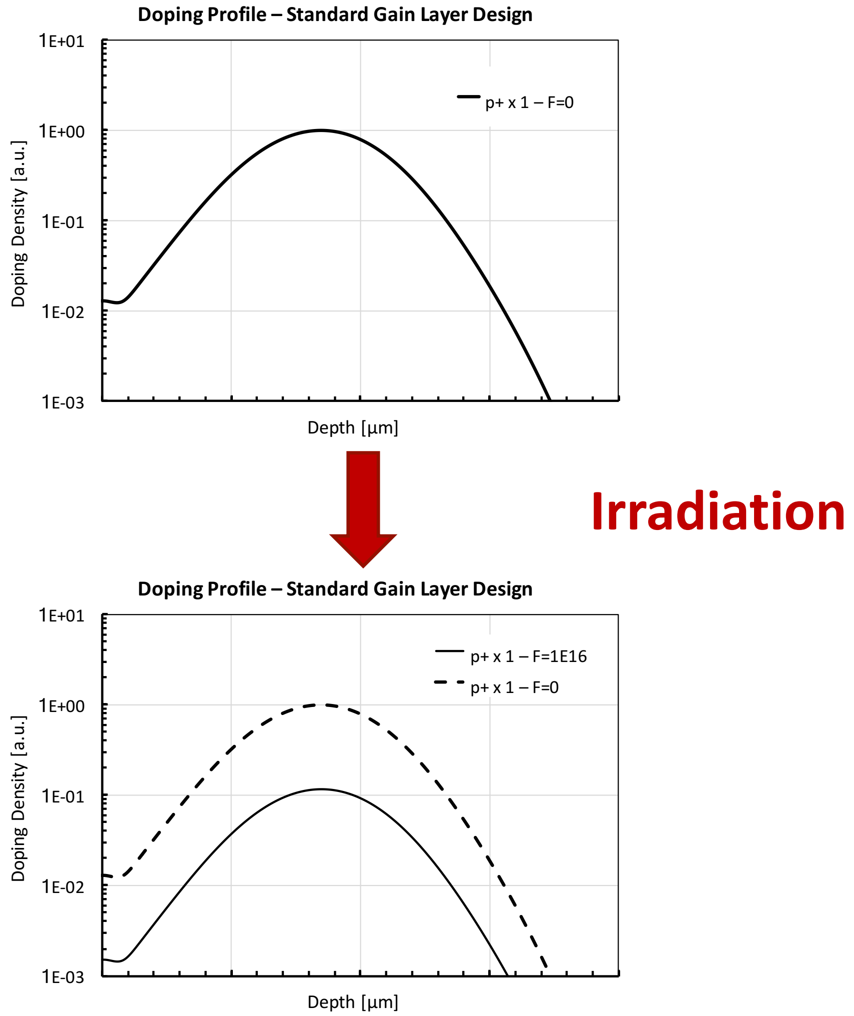
- ▻ compensation
- ▻ carbon shield
- ▻ new guard ring design
- ▻ thin substrates (15–45 µm)

Design and preparatory studies have been performed in collaboration with the Perugia group
For more details see the presentation by P. Asenov

→ The EXFLU1 sensor delivery is expected by Summer 2022

A new Paradigm – Compensation

Impossible to reach the design target with the present design of the gain layer



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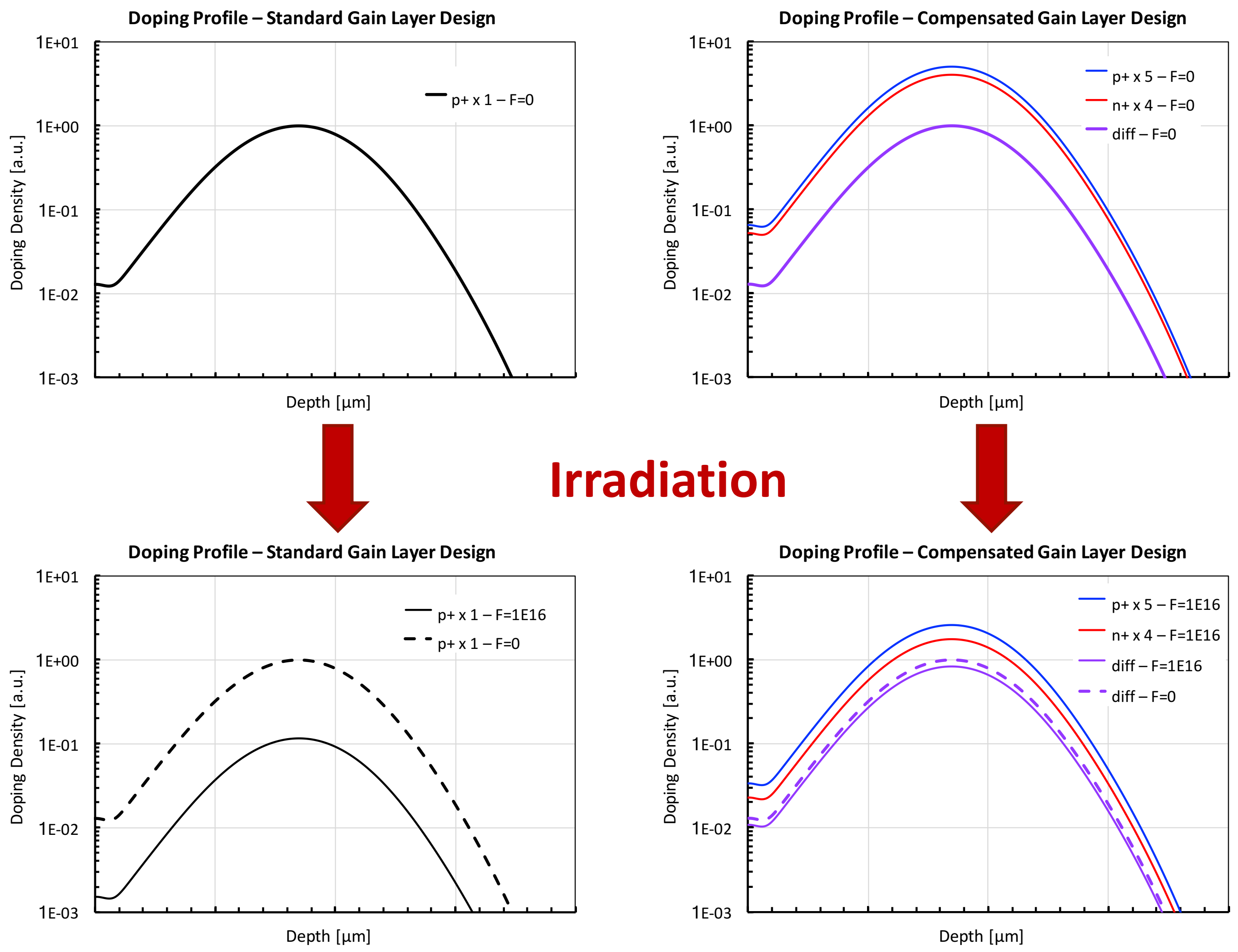
Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density



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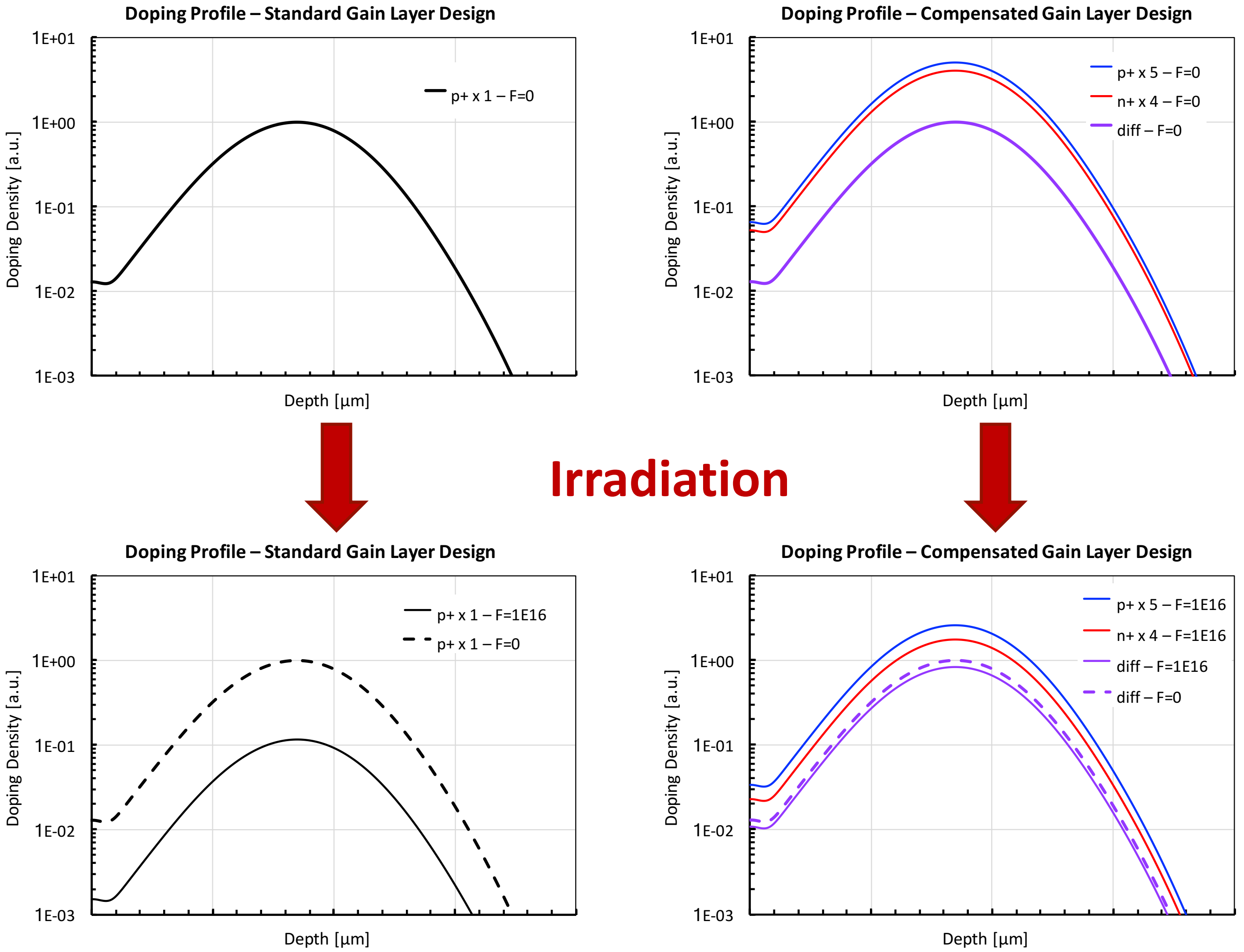

Many unknown:

- donor removal coefficient, from $n^{+}(\Phi) = n^{+}(0) \cdot e^{-c_D \Phi}$
- interplay between donor and acceptor removal (c_D vs c_A)
- effects of substrate impurities on the removal coefficients

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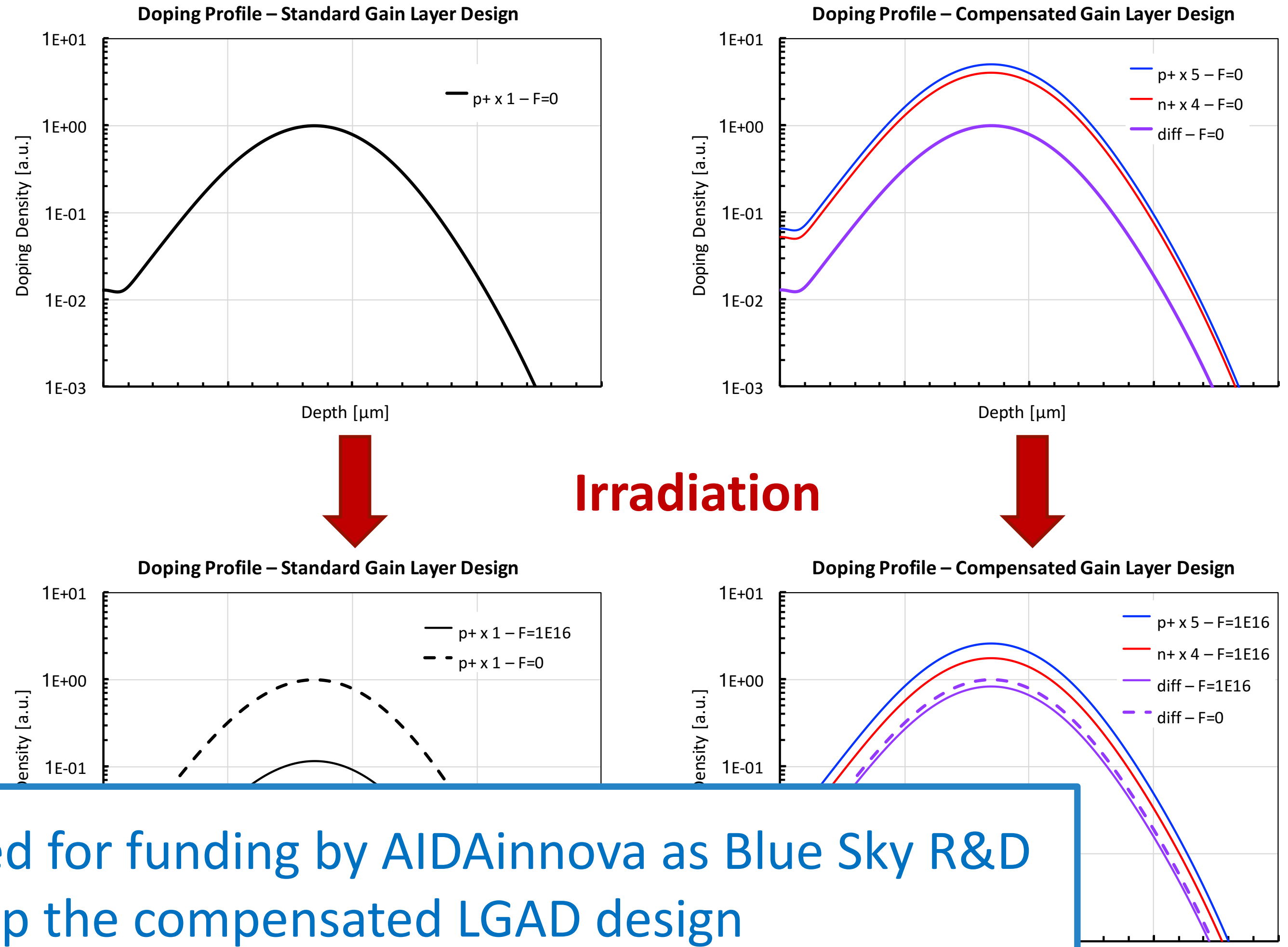
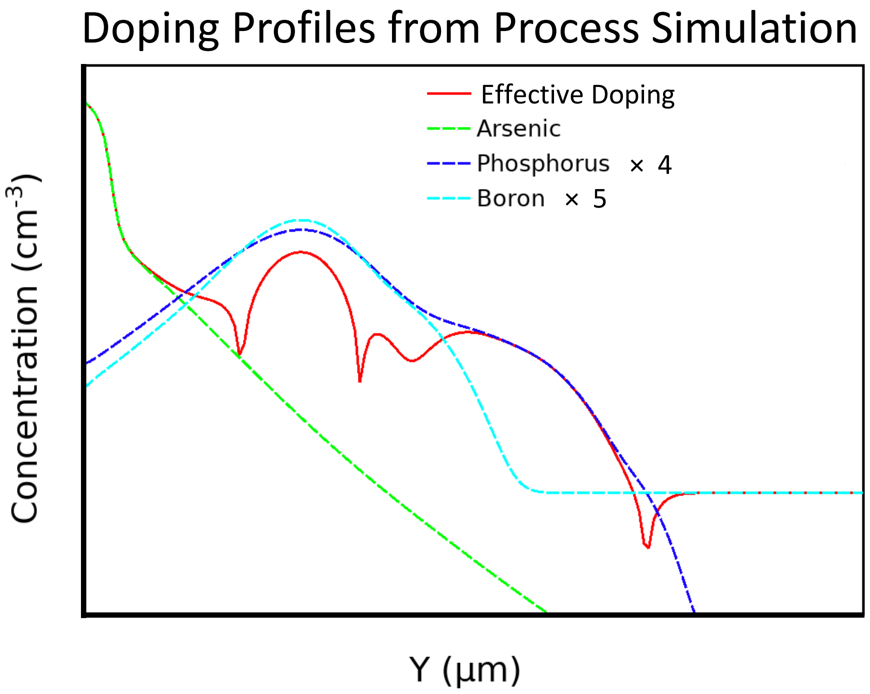


→ A 3 years project has been accepted for funding by AIDAinnova as Blue Sky R&D to investigate and develop the compensated LGAD design

Compensation in Real Life

Process simulations of Boron (p^+) and Phosphorus (n^+) implantation and activation reveal the different shape of the two profiles



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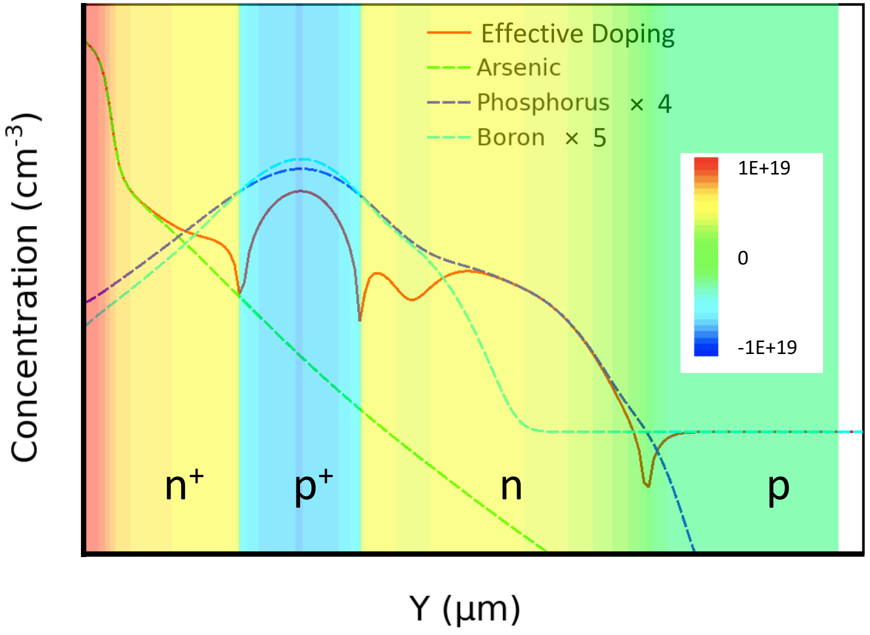
Doping Profiles from Process Simulation



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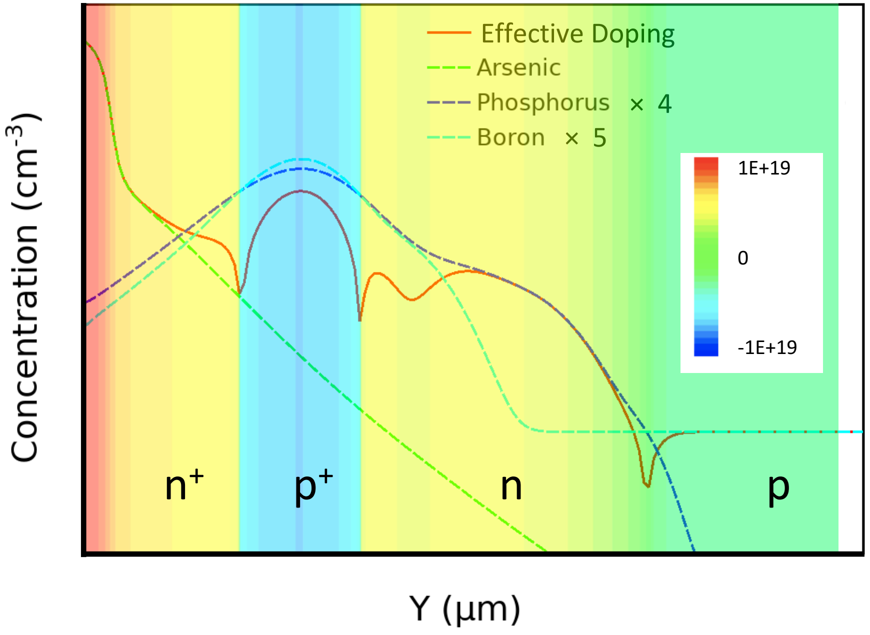
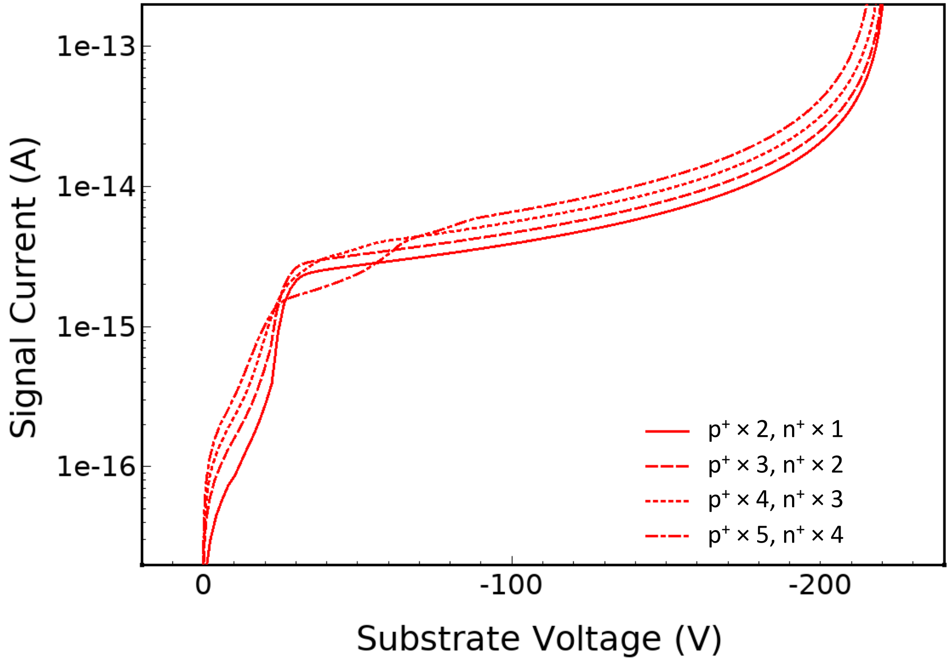


I-V from Simulation



→ The simulation of the electrostatic behaviour show that it is possible to reach similar multiplication for different initial concentrations of p^+ and n^+ dopants

Compensation – Doping Evolution with Φ

Three scenarios of net doping evolution with fluence are possible, according to the acceptor and donor removal interplay:

1. **$c_A \sim c_D$**

   p^+ & n^+ difference will remain constant $\Rightarrow$ unchanged gain with irradiation

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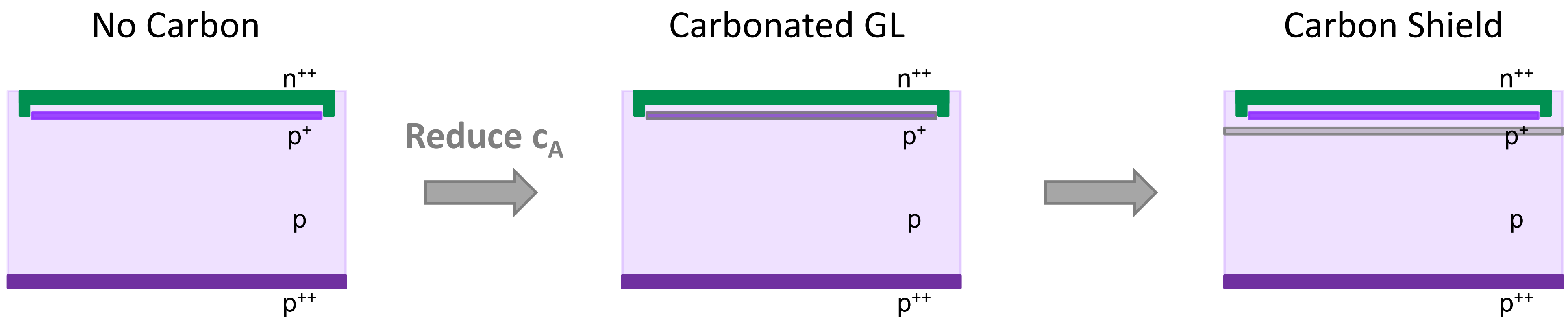
3. **$c_A < c_D$**
   n^+-atoms removal is faster $\Rightarrow$ increase of the gain with irradiation
   $\rightarrow$ **Co-implantation of Oxygen** atoms might mitigate the removal of n^+-doping

A Carbon Shield to further improve c_A

Defect engineering strategy to enhance the gain layer radiation tolerance

→ A **Carbon shield** will be infused below the gain layer volume to protect the gain layer from the diffusion of defect complexes from the bulk region and the support wafer



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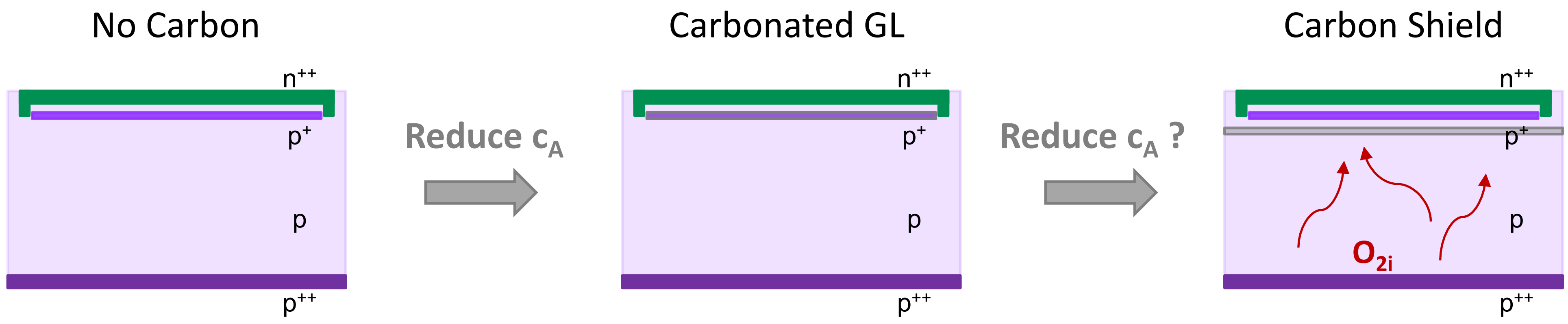
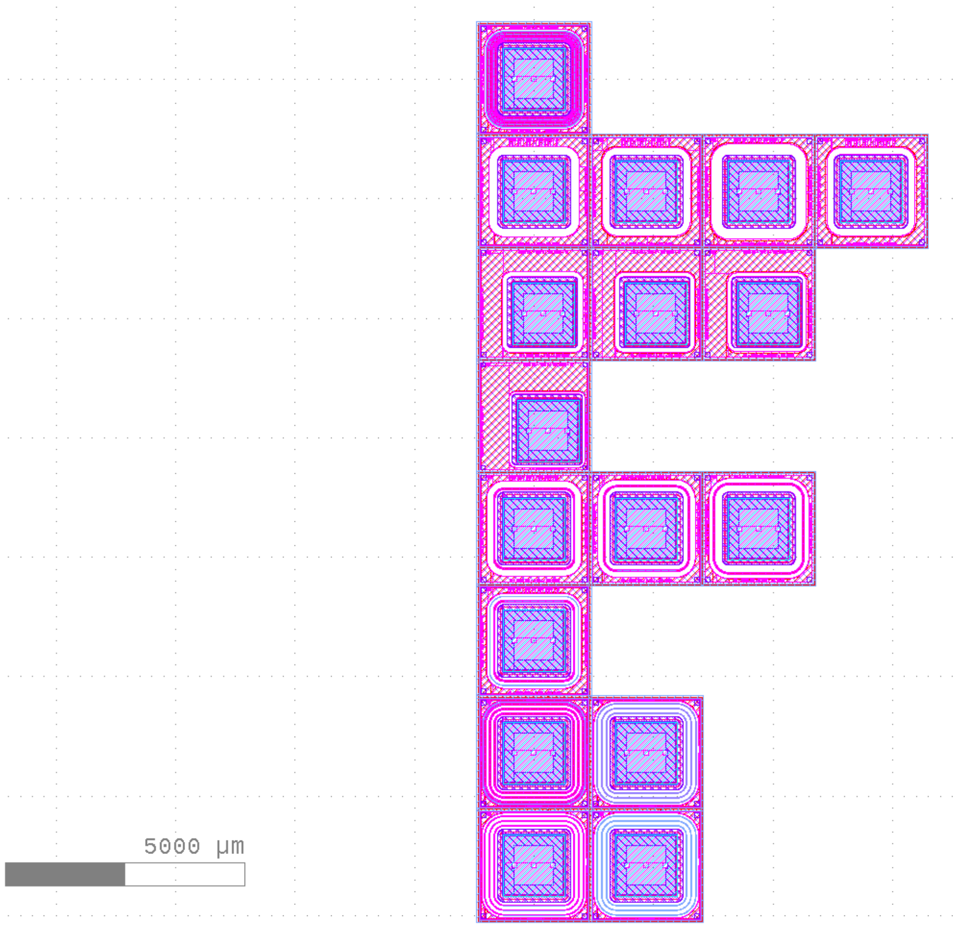


A spray of Carbon will be introduced below the gain layer region to protect the gain layer atoms from defects moving towards the n^{++} electrode during process thermal loads or exposure to particle radiation

→ Oxygen dimers can be captured by the Carbon atoms, preventing the removal of acceptors

Optimised Guard Ring Designs

16 different guard ring have been designed, optimised for thin substrates and extreme fluences

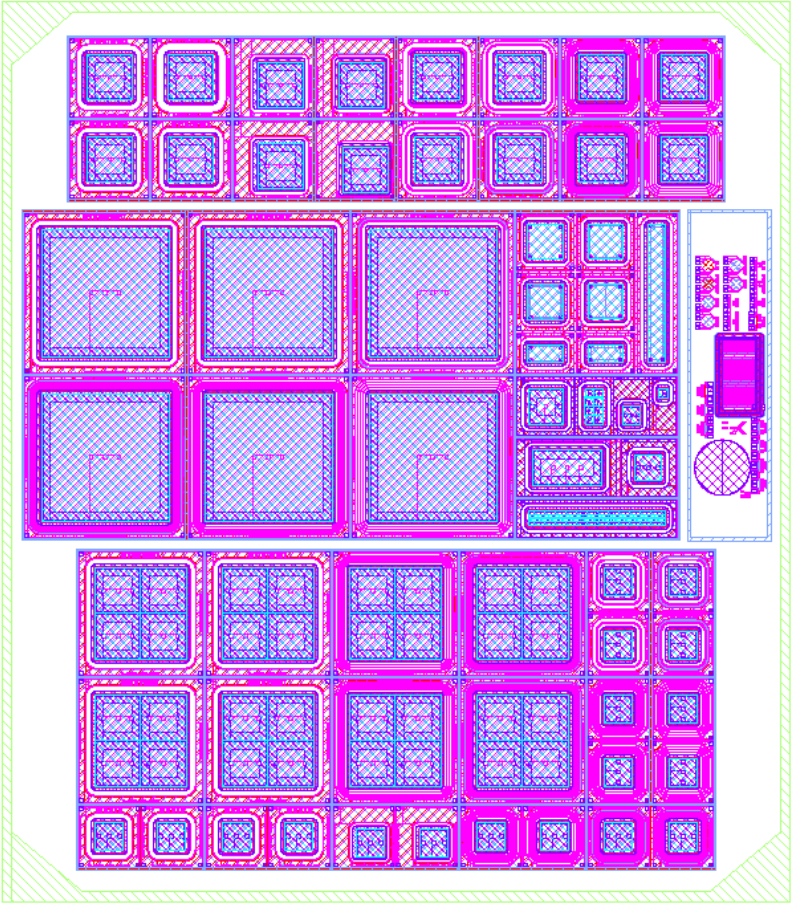


3 different guard ring strategies:

- 0 GR floating, varying the edge size
  - different size of the 'empty' region
  - different size of the edge region: 500, 300 & 200 µm
- 1 GR floating, varying the GR position
- 3 GR floating with standard design, p-stop only & n-deep only

The EXFLU1 Layout

Reticle Layout



- Single Pads with 16 different guard-ring designs
- Big Single Pads
- 2×2 Arrays & LGAD-PiNs

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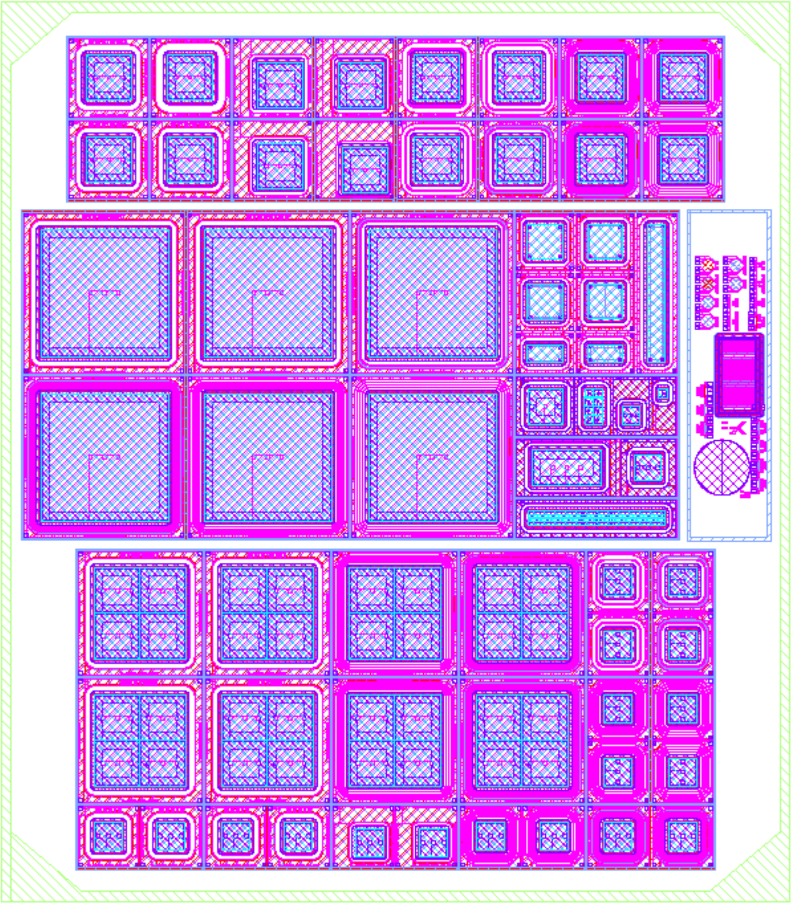
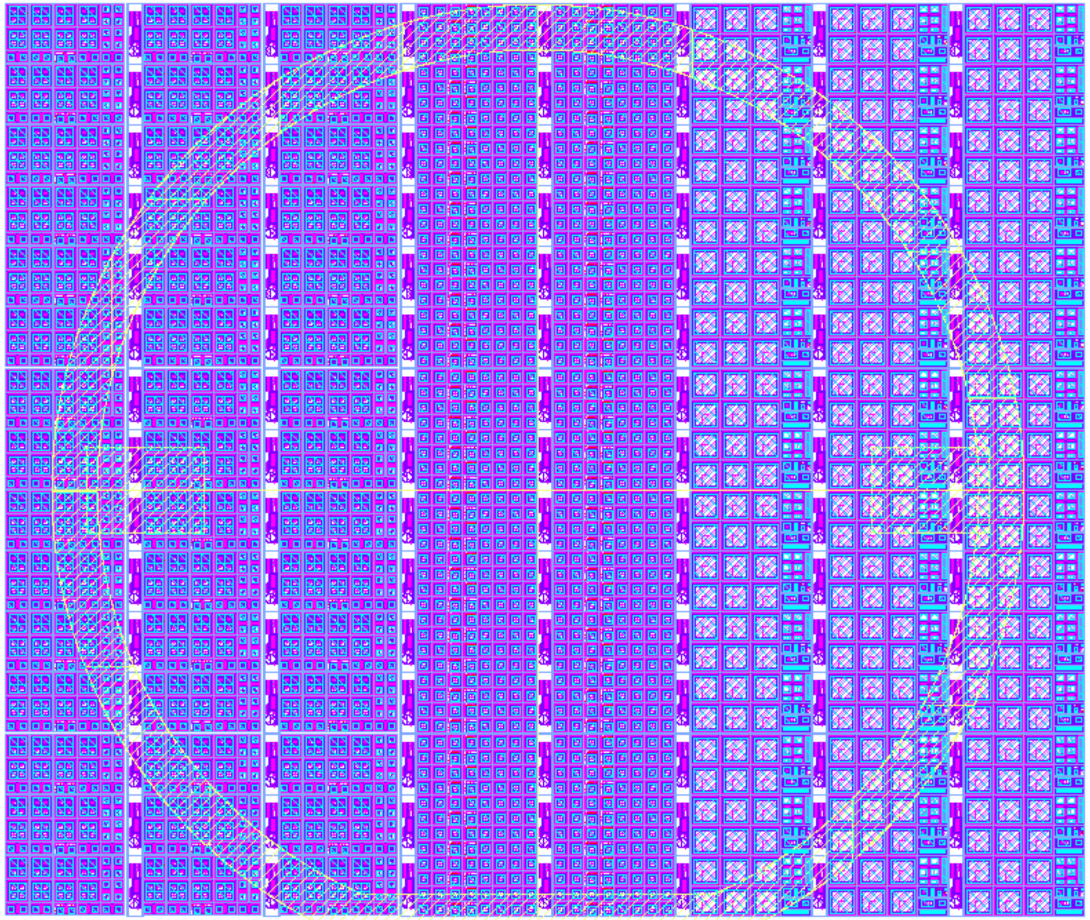


6" Wafer Layout



Towards the Extreme Fluences

→ The take-home message from the EXFLU0 production:

- ▹ signals from thin sensors are visible up to the highest fluence, namely 10^{17} n_{eq}/cm^2
- ▹ multiplication mechanism need to be preserved above 10^{16} n_{eq}/cm^2 to prevent sensors from single event burnout
- ▹ it is difficult to investigate the static behaviour of sensors irradiated to $5 \cdot 10^{16}$ n_{eq}/cm^2 and above

→ Compensation of p^+ and n^+ dopants in the gain layer volume can represent the key strategy to preserve the multiplication mechanism up to the highest fluences

→ The EXFLU1 production aims at extending the radiation resistance of thin silicon sensors and represent the proof of concept of the compensated gain layer design

⟹ Compensated gain implants will also allow extending the limit of sensors able to perform 4D tracking to fluences much above the present limit of $1–2 \cdot 10^{15}$ n_{eq}/cm^2

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Acknowledgements

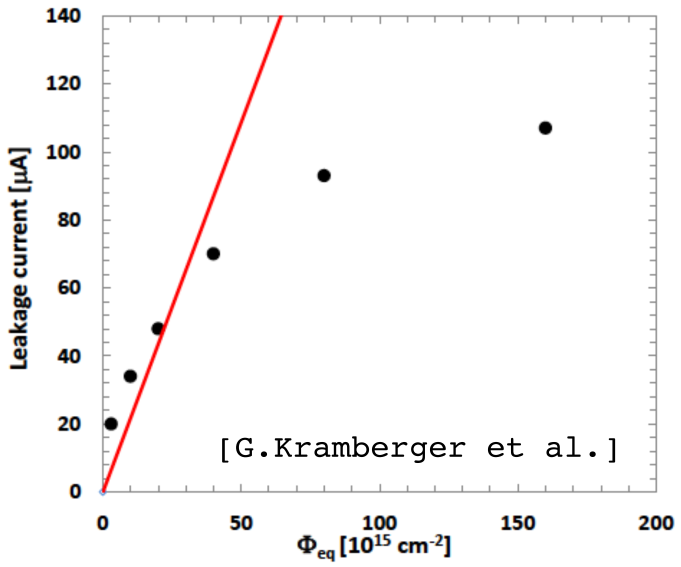
We kindly acknowledge the following funding agencies and collaborations:

- INFN CSN5
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- European Union’s Horizon 2020 Research and Innovation programme, Grant Agreement No. 101004761
- AIDAinnova, WP13
- RD50, CERN

Backup

Saturation

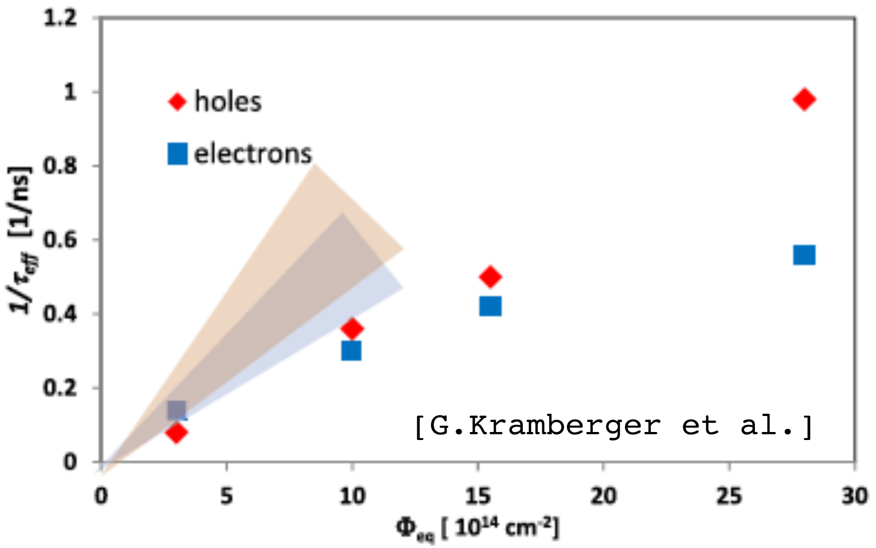
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

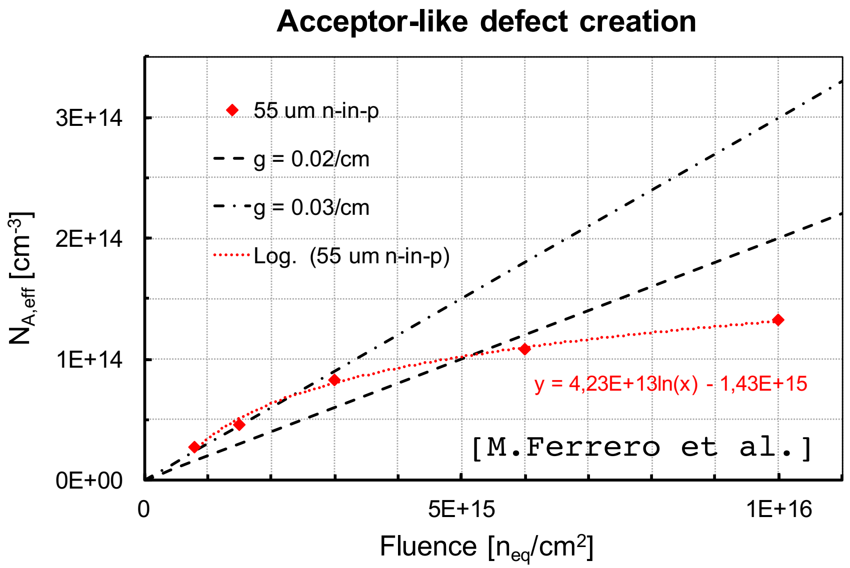
α from linear to logarithmic



Trapping probability saturation

$1/\tau_{eff} = \beta \Phi$

β from linear to logarithmic



Acceptor creation saturation

$N_{A,eff} = g_c \Phi$

g_c from linear to logarithmic

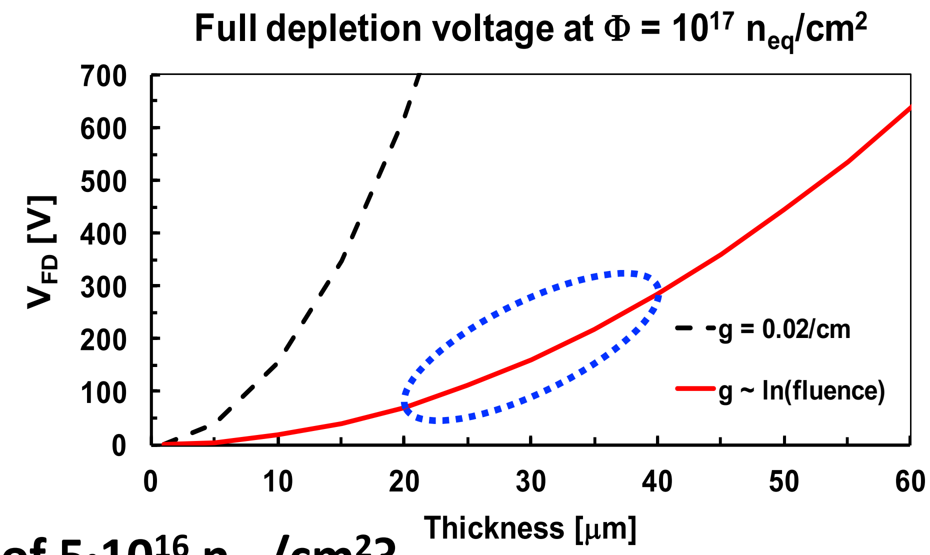
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

$$V_{FD} = e|N_{eff}|d^2/2\varepsilon$$

Saturation → N_{eff} **Reduce thickness** → d^2

At high fluences, only thin substrates can be fully depleted



What does it happen to a 25 μm sensor after a fluence of $5\cdot10^{16}$ n_{eq}/cm^2?

- It can still be depleted
- Trapping is limited (small drift length)
- Dark current is low (small volume)

However: charge deposited by a MIP ~ 0.25 fC

→ This charge is lower than the minimum charge requested by the electronics (**~ 1 fC** for tracking, $\gtrsim$ **5 fC** for timing)

→ **Need a gain of at least ~ 5** in order to efficiently record a hit

Optimal candidate: LGAD sensors

Donor Removal Characterisation

A p-in-n LGAD production batch is needed to study the donor removal coefficient, c_D

Donor removal has been studied for doping densities of $10^{12} – 10^{14}$ atoms/cm^3

We need to study donor removal in a range $10^{16} – 10^{18}$ atoms/cm^3

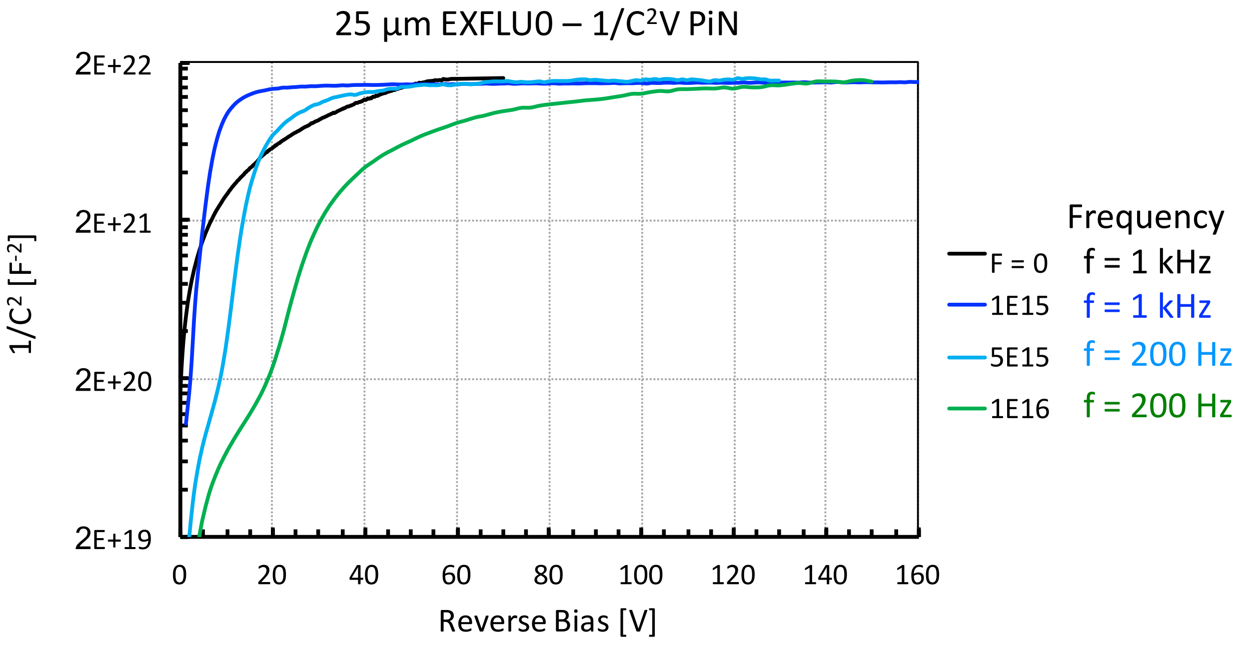
NB: Oxygen has for donor removal a very similar effect of Carbon to acceptor removal

p-in-n LGAD

→ **The main goal of the p-in-n LGAD production is to study the c_D evolution and its interplay with Oxygen co-implantation**

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



Measurements have been performed at T = +25°C

→ The goal is to extract the voltage of full depletion (V_{FD})

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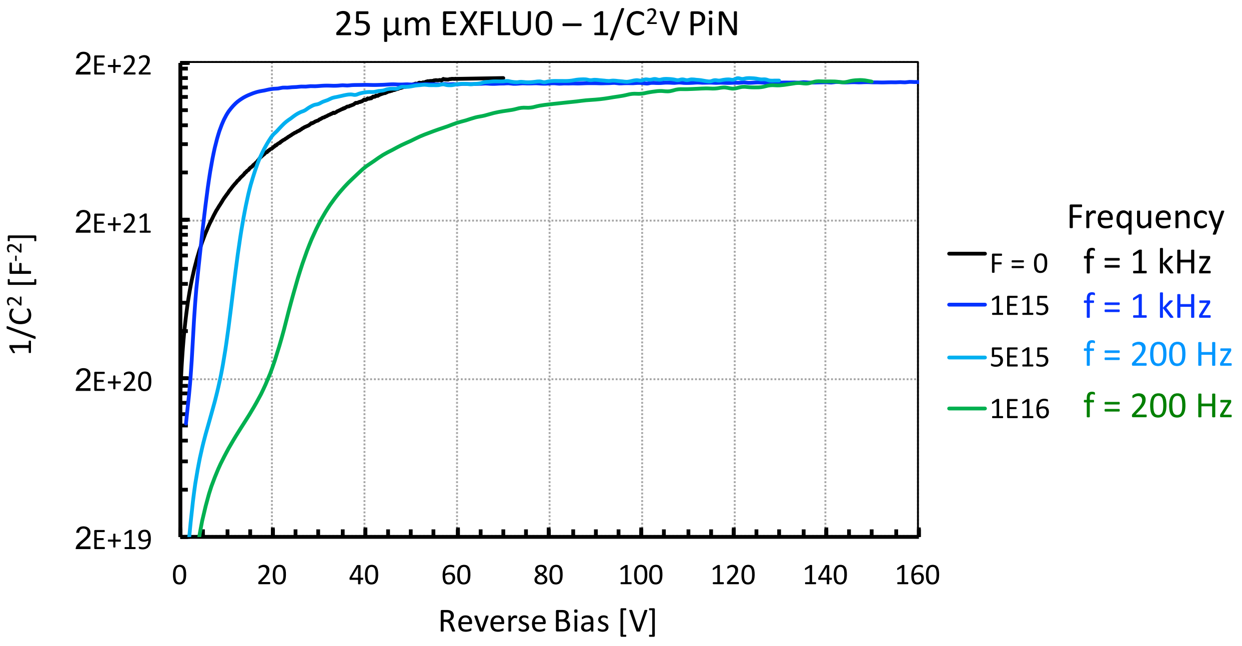

Φ $[n_{eq}/cm^2]$	V_{FD} from CV [V]
0	53
$1\cdot10^{15}$	6
$5\cdot10^{15}$	35
$1\cdot10^{16}$	82

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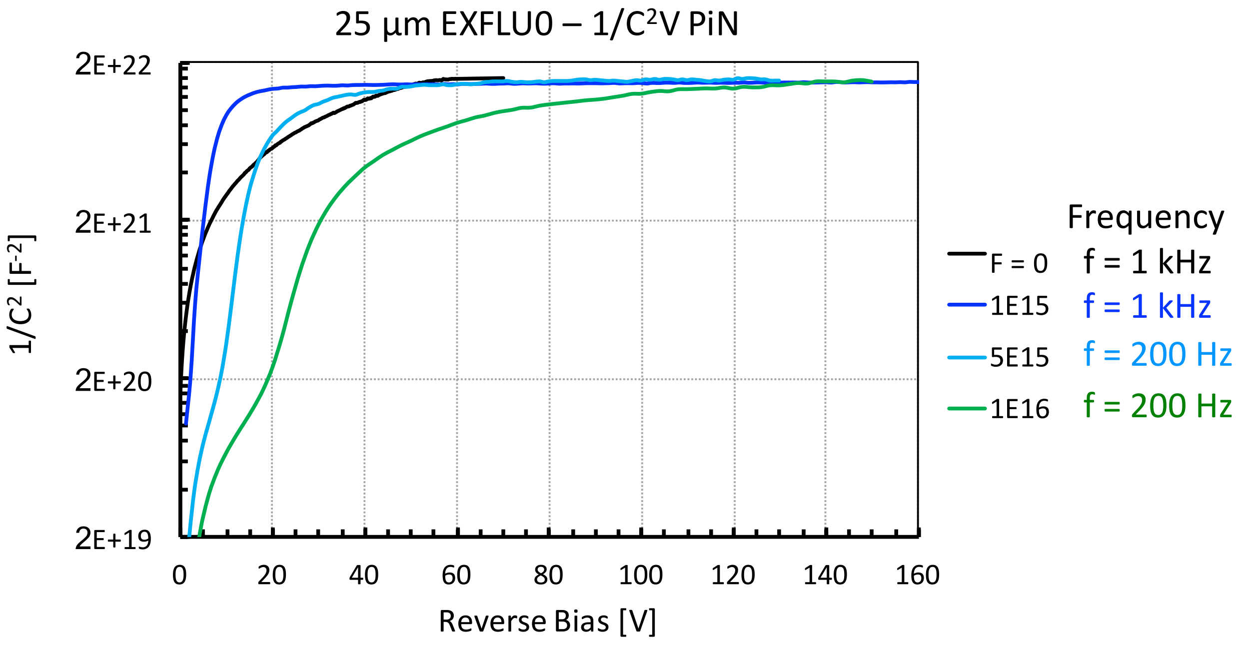


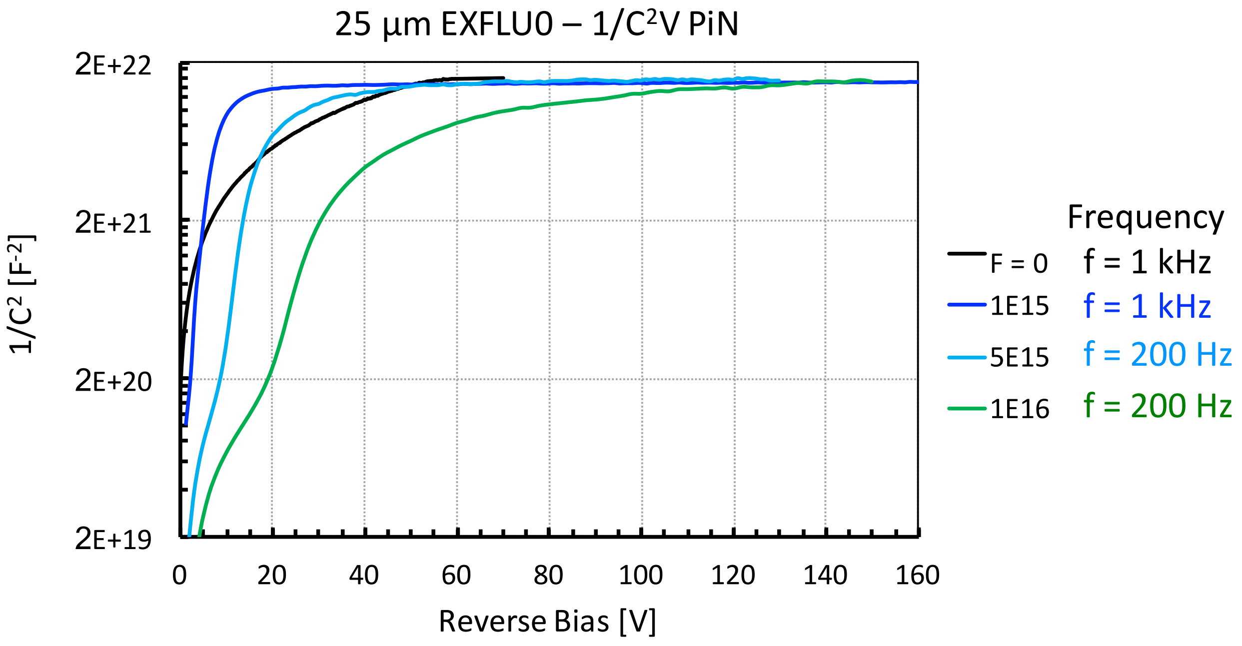
Φ [n_{eq}/cm^2]	V_{FD} from CV [V]	V_{FD} from TCT [V]
0	53	–
$1 \cdot 10^{15}$	6	–
$5 \cdot 10^{15}$	35	36
$1 \cdot 10^{16}$	82	50

Measurements have been performed at T = +25°C

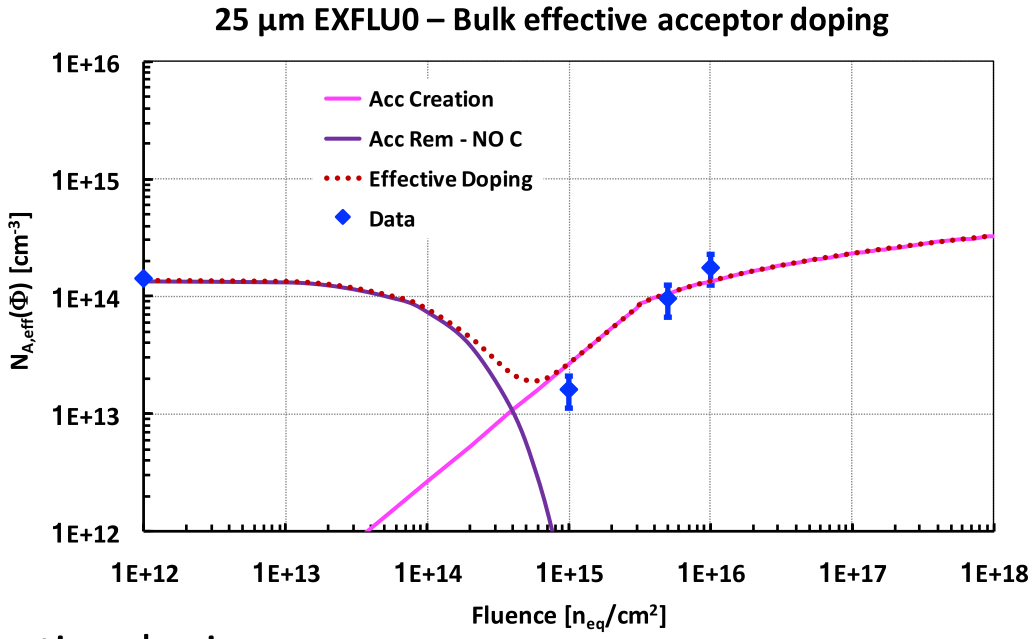
→ The average of V_{FD} from CV and TCT is used to extract the effective doping

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



From $N_{A,eff}(\Phi) = N_A(0) \cdot e^{-c\Phi} + g_c\Phi$ and considering the saturation of the acceptor creation, the 25 µm bulk doping is expected to evolve as follows



Measurements have been performed at T = +25°C

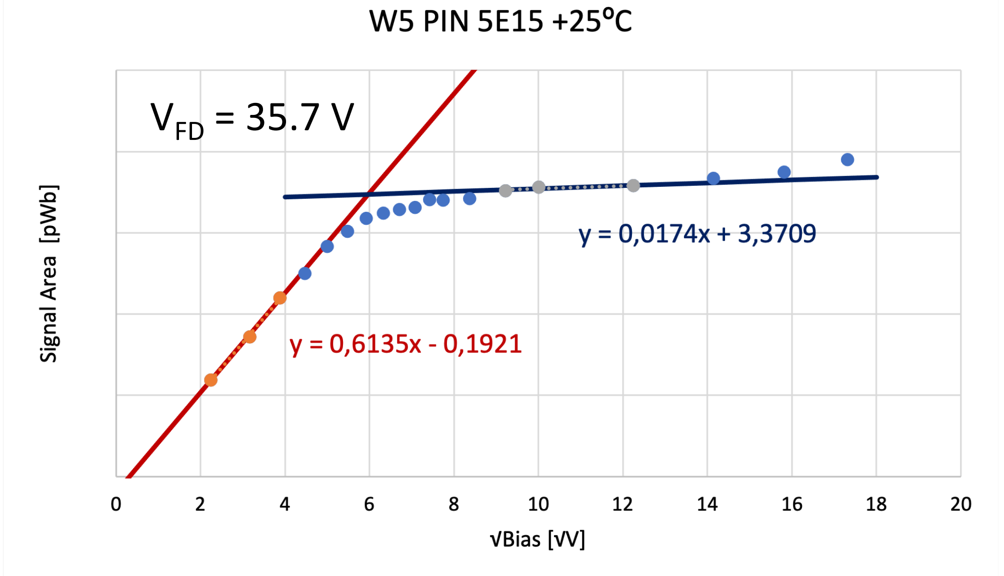
→ The average of V_{FD} from CV and TCT is used to extract the effective doping

→ Difficult to assess the voltage of full depletion above 10^{16} n_{eq}/cm^2 ⇒ Possible to use signal shape information?

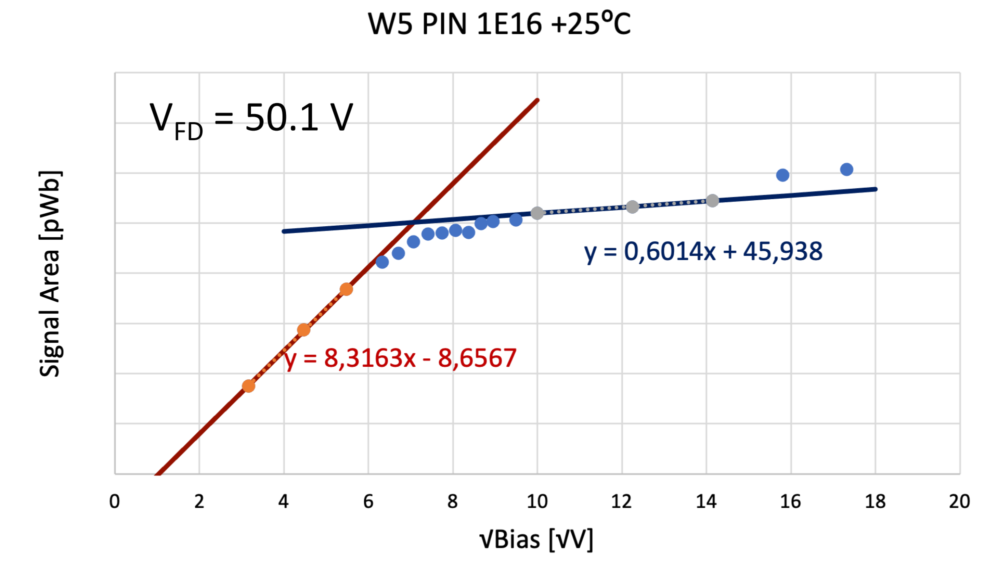
Full Depletion Voltage from TCT @ T = +25ºC

TCT on PiN @ different T to extract the voltage of full depletion

Φ = 5E15 n_{eq}/cm^2



Φ = 1E16 n_{eq}/cm^2



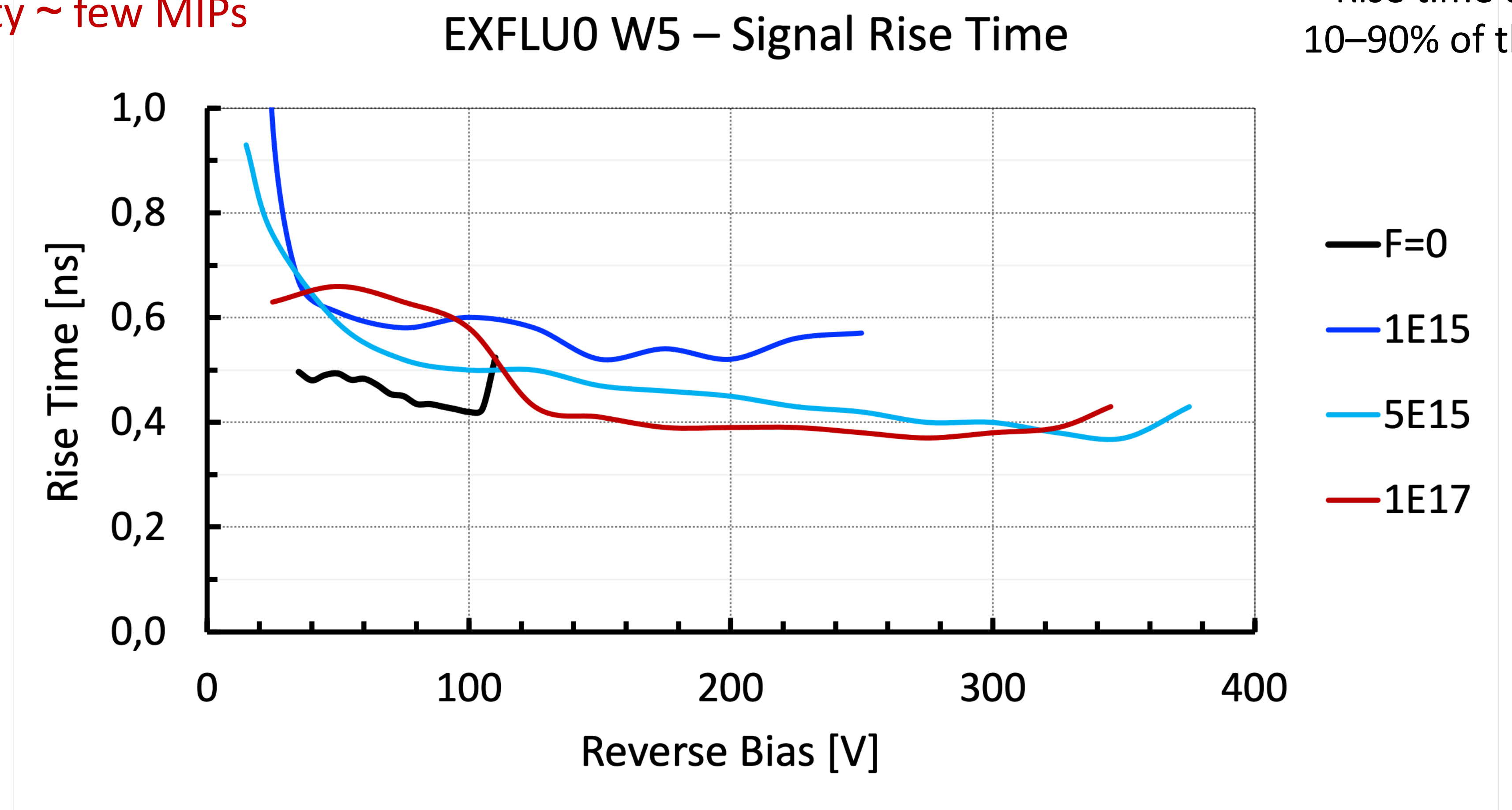
Laser intensity equivalent to many MIPs

Rise Time of LGAD @ different Fluences

Laser intensity ~ few MIPs

T = –10°C

Rise time defined as the 10–90% of the leading edge



Signals exhibit a fast rise at all fluences